NOTES AND CORRESPONDENCE

Temperature Advection: Internal versus External Processes

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ABSTRACT

Local advection of temperature is the inner product of vector velocity and spatial gradient of temperature. This product is often integrated spatially to infer temperature advection over a region. However, the contribution along an individual direction can be dominated by internal processes that redistribute heat within the domain but do not control the heat content of the domain. A new formulation of temperature advection is introduced to elucidate external heat source and sink that control the spatially averaged temperature. It is expressed as the advection of interfacial temperature relative to the spatially averaged temperature of the domain by inflow normal to the interface. It gives a total advection of temperature that is identical to the spatial integration of local temperature advection, yet the contributions along individual directions depict external processes. The differences between the two formulations are illustrated by analyzing zonal advection of near-surface temperature in the eastern equatorial Pacific during the 1997–98 El Niño and the subsequent La Niña by an ocean general circulation model. The new formulation highlights the advection of warmer water at the western side of the Niño-3 region into (out of) the region to create part of the warming (cooling) tendency during El Niño (La Niña). In contrast, the traditional formulation is dominated by the effect of tropical instability waves within the region that redistribute heat internally. The difference between the two formulations suggests a need for caution in discerning mechanisms controlling heat content of a region. Spatial integration of local temperature advection does not explain external processes that control a domain's heat content. The conclusion applies not only to the advection of oceanic temperature, but also to that of any property in any medium.

1. Introduction

Quantifying the budget of heat and other properties in the ocean is central to understanding mechanisms of ocean circulation and its role in the earth's climate system. Ocean current plays an important role in regulating these budgets in many regions of the world's ocean. The advective component of temperature tendency,

$$-\mathbf{V}\cdot\boldsymbol{\nabla}T = (-u\partial T/\partial x - \upsilon\partial T/\partial y - w\partial T/\partial z),$$

has often been used to examine the relative magnitudes of individual directional contributions of ocean currents in local temperature balance (e.g., Stevenson and Niiler 1983; Schiller et al. 2000; Wang and McPhaden 2001; Foltz et al. 2003). Here vector $\mathbf{V}$ is velocity with directional elements u, υ, and w, in the zonal (x), meridional (y), and vertical (z) directions, respectively, T is temperature, and $\boldsymbol{\nabla}$ is the spatial gradient operator. However, a spatial integration of the individual directional elements of $-\mathbf{V}\cdot\boldsymbol{\nabla}T$ can be dominated by processes that redistribute heat within the integrated domain and, thus, do not affect the spatially averaged temperature (or heat content) of the domain.

For instance, consider a simple two-dimensional flow described in Fig. 1 that is the upper branch of an idealized meridional overturning circulation of the ocean. The northern and southern walls of the reservoir are impermeable and adiabatic. For simplicity, we assume a stationary circulation in this upper layer with upwelling at the southern end, followed by northward flow and downwelling at the northern end. The atmosphere heats (cools) the upper layer of the ocean at the southern (northern) end. The temperature of water decreases toward the north. The average temperature of this upper layer is in balance between heat flux at the sea surface and vertical exchange through the lower boundary at the northern and southern ends. Meridional advection is not explicitly part of this global balance because there is no meridional heat flux across the northern and southern walls. Yet, the volume integral of meridional advection, $-\upsilon\partial T/\partial y$, is not zero, reflecting a northward redistribution of heat within the domain. Such an internal redistribution of heat does not explain the external processes that control the mean temperature of the domain.

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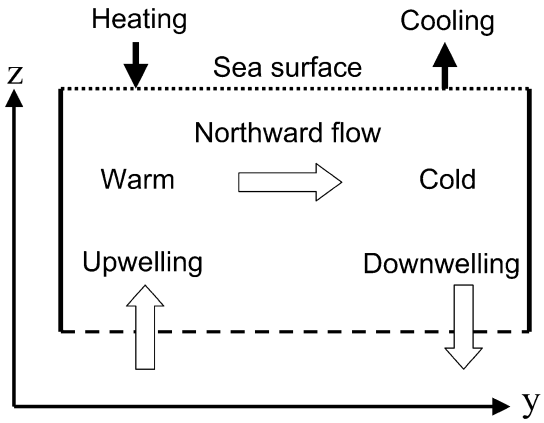

FIG. 1. The upper branch of an idealized meridional overturning circulation to illustrate the heat balance.

In this study, we explore an alternate formulation of temperature advection so as to evaluate individual external processes that control the domain's spatially averaged temperature. Details of the new formulation are described in section 2. In section 3, the differences between the two formulations are illustrated by applying them to analyze zonal advection of near-surface temperature in the eastern equatorial Pacific Ocean. These differences mark a stark contrast between local and external temperature advection as described by the two formulations, respectively. The findings are summarized in section 4.

2. A new formulation of temperature advection to reflect external processes

Alternative to the gradient form of advective tendency discussed in section 1, the integration of the flux form of the advective tendency, $-\nabla \cdot (\mathbf{V}T) = -\partial(uT)/\partial x - \partial(vT)/\partial y - \partial(wT)/\partial z$, does not depend on internal redistribution as $-\mathbf{V} \cdot \nabla T$ does, but only on the temperature flux through the domain boundaries:

$$-\iiint_D \nabla \cdot (\mathbf{V}T)\, dx\, dy\, dz = -\int_S (\mathbf{V} \cdot \mathbf{n})T\, dS,$$

where S is the bounding surface of the domain D and $\mathbf{n}$ is the unit normal vector of the interface (pointing outward). The expression $-\int_S (\mathbf{V} \cdot \mathbf{n})T\, dS$ describes the advective temperature flux across the entire bounding interface of D. From its appearance, $-\int_S (\mathbf{V} \cdot \mathbf{n})T\, dS$ seems to be ambiguous because T depends on the arbitrary reference of zero temperature. However, it is easy to show that it is actually unambiguous because of mass conservation: let T_{ref} represents an arbitrary scalar reference to zero temperature, then

$$\begin{aligned}-\int_S (\mathbf{V} \cdot \mathbf{n})(T - T_{\text{ref}})\, dS &= -\int_S (\mathbf{V} \cdot \mathbf{n})T\, dS \\ &\quad + T_{\text{ref}} \int_S (\mathbf{V} \cdot \mathbf{n})\, dS \\ &= -\int_S (\mathbf{V} \cdot \mathbf{n})T\, dS\end{aligned}$$

because of mass conservation $\int_S (\mathbf{V} \cdot \mathbf{n})\, dS = 0$.

It is often necessary to understand heat advection along a certain direction or through a partial interface in order to understand various external processes that control the heat content of the domain. Unfortunately, temperature flux through a partial interface A, $-\int_A (\mathbf{V} \cdot \mathbf{n})T\, dS$, is ambiguous because mass is usually not conserved through a partial interface: $\int_A (\mathbf{V} \cdot \mathbf{n})\, dS \neq 0$ and thus

$$\begin{aligned}-\int_A (\mathbf{V} \cdot \mathbf{n})(T - T_{\text{ref}})\, dS &= -\int_A (\mathbf{V} \cdot \mathbf{n})T\, dS \\ &\quad + T_{\text{ref}} \int_A (\mathbf{V} \cdot \mathbf{n})\, dS \\ &\neq -\int_A (\mathbf{V} \cdot \mathbf{n})T\, dS\end{aligned}$$

(i.e., dependent on the reference to zero temperature). For this reason, temperature flux across a section evaluated as $\int_A (\mathbf{V} \cdot \mathbf{n})T\, dS$ is a meaningful estimate of heat transport only if there is no net mass flux across the section (e.g., Montgomery 1974; Hall and Bryden 1982).

As Montgomery (1974) and Hall and Bryden (1982) pointed out, the purpose of mass conservation is to make the absolute temperature flux unambiguous by removing the dependence on zero-temperature reference from $\int_A (\mathbf{V} \cdot \mathbf{n})T\, dS$. However, a meaningful evaluation of the relative magnitude of temperature advection across various parts of the bounding surface is still possible by considering the anomalous temperature that is advected to or from the domain. Heat advection across a partial interface can change the domain's average temperature if, and only if, the interface temperature is different from that of the domain's average. Therefore we define temperature flux relative to the domain's average temperature, namely, $-\int_A (\mathbf{V} \cdot n)(T - T_m)\, dS$, where A is an arbitrary partial interface of volume D and T_m is the volume-averaged temperature of the domain,

$$T_m = \iiint_D T\, dx\, dy\, dz/V_D$$

(where V_D is the volume of the domain). In the following, T_m is simply referred to as mean temperature of the domain. The above expression represents temperature flux into the domain with interface temperature referenced to the mean temperature of the domain. Unlike the conventional boundary flux form $-\int_A (\mathbf{V}\cdot\mathbf{n})T\,dS$, it is independent of the reference to zero temperature because $T - T_m$ eliminates the common reference. The expression $-\int_A (\mathbf{V}\cdot\mathbf{n})(T - T_m)\,dS$ is therefore unambiguous despite the fact that there may be a nonzero net mass flux through the partial interface A. If the temperature of water advected across A were identical to the mean temperature of domain D, our formulation $-\int_A (\mathbf{V}\cdot\mathbf{n})(T - T_m)\,dS$ would result in zero heat advection because $T = T_m$. However, the conventional boundary flux form $-\int_A(\mathbf{V}\cdot\mathbf{n})T\,dS$ would still be nonzero because T is referenced to an arbitrary reference to zero temperature instead of to the mean temperature of the domain. Our choice of reference temperature to be the domain's mean temperature T_m is a sensible and unique one because our goal is to evaluate the impact of heat advection on the mean temperature (or heat content) of the subject domain.

As mentioned earlier, our proposed formulation of heat advection does not require zero net mass flux across a section in order to be unambiguous because it is by construct independent of the arbitrary reference of zero temperature. There are, in fact, other examples of evaluating heat transport when mass is not conserved. For example, in their reply to Montgomery (1974), Niiler and Richardson decomposed the seasonal change of temperature flux across the Florida channel into time mean $(\overline{\ })$ and anomaly $(')$: $(VT)_{\text{summer}} - (VT)_{\text{winter}} \cong 2[(V'\overline{T}) + (\overline{V}T')]$ (see Montgomery 1974, p. 535). While the first term $(V'\overline{T})$ was not meaningful due to its dependence on zero-temperature reference, they suggested that the second term $(\overline{V}T')$ was unambiguous and meaningful because T' eliminated the common reference. This despite the fact that $\overline{V}$ across the Florida channel is not zero. That is essentially because the temperature in one season is referenced to that in another season, and so the common reference to zero temperature is eliminated. Their argument is similar to our discussion that zero mass flux is not required as along as one can make the temperature advection independent of zero-temperature reference. A similar argument applies to the gradient form of local temperature advection $u\partial T/\partial x$. Clearly, u has to be generally balanced by v and w instead of by u itself. The reason that $u\partial T/\partial x$ can be discussed separately from $v\partial T/\partial y$ and $w\partial T/\partial z$ is because it is independent of zero-temperature reference. In this case, the temperature at one point is referenced to that immediately to the west or east. Note that our formulation $u(T - T_m)$ is equivalent to $u\partial T/\partial x$ when the box is very small.

When integrated across the entire bounding surface of the domain, our proposed formulation of heat advection results in a total value that is identical to the spatial integration of the flux form of heat advection $-\nabla\cdot(\mathbf{V}T)$:

$$
\begin{aligned}
-\int_S (\mathbf{V}\cdot\mathbf{n})(T - T_m)\,dS &= -\int_S (\mathbf{V}\cdot\mathbf{n})T\,dS \\
&\quad - T_m \int_S (\mathbf{V}\cdot\mathbf{n})\,dS \\
&= -\iiint_D \nabla\cdot(\mathbf{V}T)\,dx\,dy\,dz.
\end{aligned}
$$

The last equality is valid because of volume conservation over the entire bounding surface, $\int_S (\mathbf{V}\cdot\mathbf{n})\,dS = 0$ (note that for a model using the Boussinesq appriximation such as ours, a box that includes the sea surface as a partial bounding surface would still satisfy volume conservation). This in turn is identical to integrating local temperature advection, $-\mathbf{V}\cdot\nabla T$, over the entire volume:

$$
\begin{aligned}
-\iiint_D \nabla\cdot(\mathbf{V}T)\,dx\,dy\,dz &= -\iiint_D (\mathbf{V}\cdot\nabla T)\,dx\,dy\,dz \\
&\quad -\iiint_D T(\nabla\cdot\mathbf{V})\,dx\,dy\,dz \\
&= -\iiint_D (\mathbf{V}\cdot\nabla T)\,dx\,dy\,dz
\end{aligned}
$$

because $\nabla\cdot\mathbf{V} = 0$. Although

$$
-\int_S (\mathbf{V}\cdot\mathbf{n})(T - T_m)\,dS = -\iiint_D \mathbf{V}\cdot\nabla T\,dx\,dy\,dz,
$$

as we shall see in the next section, the directional components of these two formulations (i.e., the boundary flux referenced to the mean temperature and the spatial integration of local gradient form) can be very different because of different physical processes that they represent.

3. Examples illustrating internal and external processes of heat advection

To illustrate the differences between the two formulations, we apply the two formulations to the analysis of temperature advection in the upper eastern equatorial Pacific as simulated by a data-assimilative model for the period of 1997–2000. This period encompasses the 1997–98 El Niño and the subsequent La Niña. The ocean general circulation model is the same as that used by Lee et al. (2002) with somewhat different background mixing coefficients. Briefly, the model is a near-global version of the Massachusetts Institute of Technology ocean general circulation model (Marshall et al. 1997). It has a horizontal resolution of $1° \times 0.3°$ in the Tropics and $1° \times 1°$ in the extratropics. There are 46 vertical levels with a depth increment ranging from 10 m above 150 m to intervals of 400 m at depth. Sea level

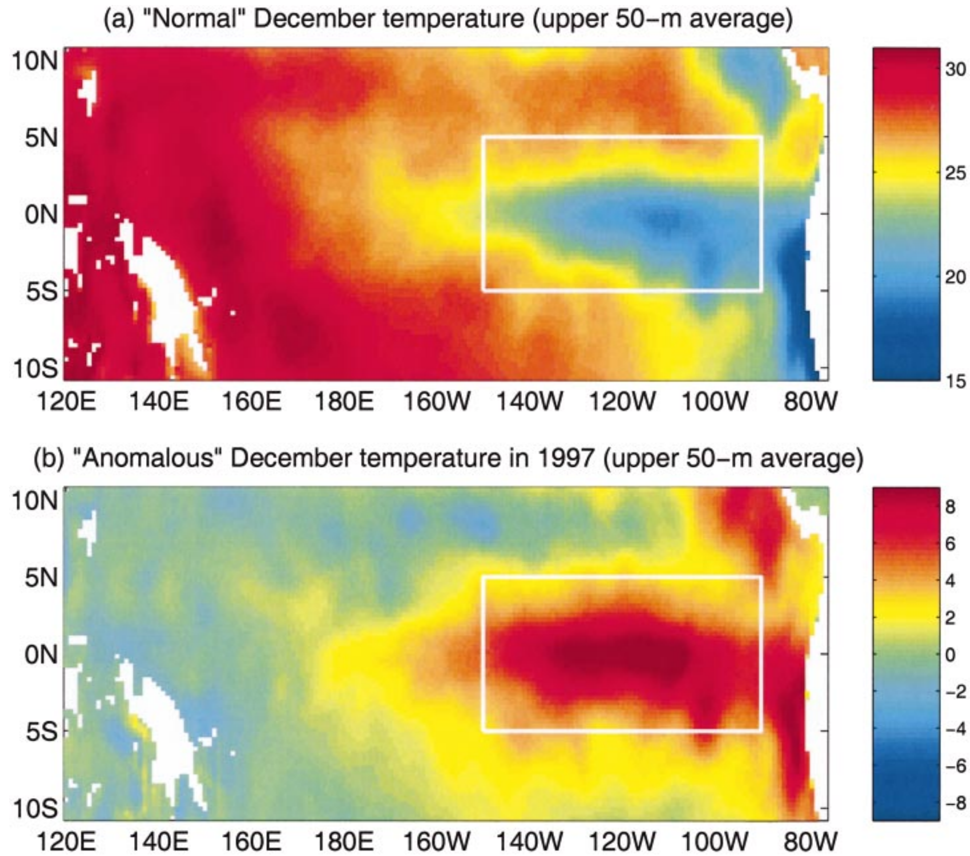

FIG. 2. December temperature averaged over the model's upper 50 m: (a) mean from 1997 to 2000 and (b) anomaly in 1997 relative to (a). The region enclosed by the white lines is the Niño-3 area.

anomalies observed by the Ocean Topography Experiment (TOPEX)/Poseidon altimeter during the period of 1997–2000 are assimilated into the model using the adjoint method by adjusting the prior initial condition and surface forcings. Further description of the assimilation procedure is provided in Lee and Fukumori (2003). The assimilation is part of the Estimating the Circulation and Climate of the Ocean (ECCO) consortium effort (see online at http://www.ecco-group.org). The consortium activity has been discussed by Stammer et al. (2002). The assimilation product used for the analysis is available through a Live Access Server online (at http://eyre.jpl.nasa.gov/las). ECCO assimilation products are characterized by their physical consistency in terms of closed budgets (e.g., temperature budget).

Figure 2a shows the model's mean December temperature of the equatorial Pacific Ocean averaged in the top 50 m. The figure illustrates the large zonal temperature difference between the warm pool in the west and the cold tongue in the east. The mature stage of the 1997–98 El Niño is characterized by anomalous warming in eastern equatorial Pacific in December 1997 (Fig. 2b). For the sake of simplicity, the domain of analysis is chosen to be the top 50 m of the so-called Niño-3 region (5°S–5°N, 150°–90°W) as enclosed by the white lines. The time series of nonseasonal anomaly (i.e., with the 1997–2000 averaged seasonal cycle removed) of temperature averaged over this domain is presented in Fig. 3a. The temperature increases during most of 1997 (positive tendency) and generally decreases during 1998 (negative tendency), indicating the development of the 1997–98 El Niño and the subsequent La Niña events. In the following, we examine contributions of zonal advection to changes in Niño-3 temperature as an example of illustrating the differences between the traditional formulation of advection and the new formulation described in section 2.

The averaged zonal advective tendencies for the mean temperature of Niño-3 are

$$-\iiint_D (u\partial T/\partial x)\ dx\ dy\ dz/V_D$$

for the traditional formulation and

$$\iint_{Sw} u(T - T_m)\ dy\ dz/V_D - \iint_{Se} u(T - T_m)\ dy\ dz/V_D$$

for the new formulation, where Sw and Se denote the western and eastern interface of the Niño-3 box, re-

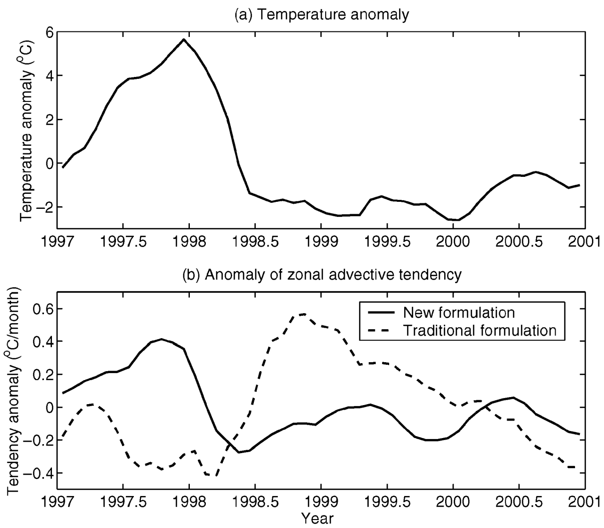

FIG. 3. Interannual anomaly of (a) temperature averaged over the top 50 m of the Niño-3 region and (b) zonal advective tendencies computed from the traditional and the new formulations.

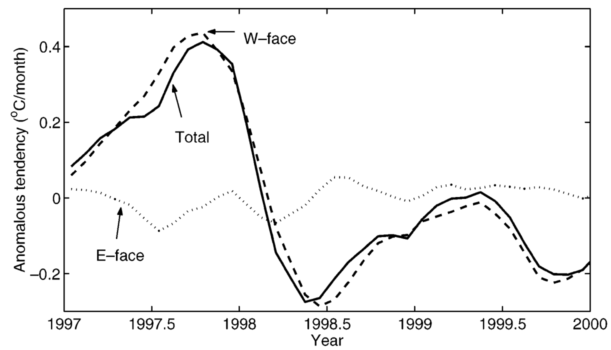

FIG. 4. Total anomaly of zonal advection computed from the new formulation (solid curve) and the contributions from the western and eastern interfaces (dashed and dotted curves, respectively).

spectively. Anomalies of these tendencies relative to their respective mean annual cycles are shown in Fig. 3b by the dashed and solid curves for the traditional and new formulations, respectively. For the new formulation, the zonal advective tendency is positive in 1997 and negative in most of 1998, suggesting that zonal advection contribute positively to the warming and cooling of mean temperature over the Niño-3 area associated with the warming phase of the El Niño in 1997 and the decay in 1998, respectively. However, the traditional form shows a cooling tendency for most of 1997 and the first several months of 1998 (El Niño condition), and a warming tendency from mid-1998 to early 2000 (La Niña condition).

To help to understand why the new formulation gives a warming (cooling) tendency in 1997 (1998), we further analyze individual contributions from the western and eastern interfaces (Fig. 4). The contribution from the western interface,

$$\left[\iint_{Sw} u(T - T_m)\, dy\, dz\right]' \Big/ V_D,$$

where the prime denotes nonseasonal anomaly, is seen to be the dominant term between the two zonal advections. To examine the relative role of anomalies in circulation and temperature, we decompose u and $\delta T = T - T_m$ at the western interface into the corresponding averaged seasonal cycles (represented by an overbar) and nonseasonal anomalies (denoted by a prime): $u = \overline{u} + u'$ and $\delta T = \overline{\delta T} + \delta T'$. Then,

$$u(T - T_m) \equiv u\delta T = u'\overline{\delta T} + \overline{u}\delta T' + u'\delta T' + \overline{u}\overline{\delta T}.$$

The four terms correspond to, respectively, the advection of mean (seasonal) temperature difference by anomalous flow, the advection of anomalous temperature difference by mean (seasonal) flow, the advection of anomalous temperature difference by anomalous flow, and the advection of mean (seasonal) temperature difference by mean (seasonal) flow. Defining the interfacial integration $\langle\ \rangle = \iint_{Sw} dy\, dz/V_D$, the contribution from the western face $[\iint_{Sw} u(T - T_m)\, dy\, dz]'/V_D$ can then be written as

$$\langle u\delta T\rangle' = \langle u'\overline{\delta T}\rangle' + \langle \overline{u}\delta T'\rangle' + \langle u'\delta T'\rangle'.$$

The time series of these quantities are presented in Fig. 5. The total anomaly $\langle u\delta T\rangle'$ (the black curve) is contributed primarily by $\langle u'\overline{\delta T}\rangle'$ (the red curve). Therefore, the dominant zonal advection term affecting interannual temperature anomalies in Niño-3 is the advection of mean (seasonal) zonal temperature difference $\overline{\delta T}$ by anomalous zonal currents at the western interface. Anomalous zonal currents are known to be associated with the weakening (strengthening) of the trade winds over the tropical Pacific during 1997 (1998). Intuitively, one could interpret this effect by the following: 1) anomalous eastward flow brings warmer water from the west into the Niño-3 region to create a warming tendency during El Niño and 2) anomalous westward flow takes out warmer water from the western side of the Niño-3 region to create a cooling tendency during La Niña.

The important role of $\langle u'\overline{\delta T}\rangle'$ is in agreement with the finding of Picaut et al. (1996) who suggested that interannual variability of sea surface temperature (SST) in the central to eastern equatorial Pacific could be explained by the zonal displacement of the eastern edge of the warm pool due to advection by anomalous surface current. In fact, our analysis (not shown) suggests that zonal advection of temperature is even larger if the analysis domain is chosen to be the central equatorial Pacific (not shown). This is not to say that zonal advection is more important than meridional and vertical advection, but merely to explain the role of zonal advection in changing Niño-3 temperature.

A complete heat balance analysis for the Niño-3 region is not the intent of this study. However, anomalies of temperature advection through various faces of the Niño-3 box are shown in Fig. 6 so that one can get a

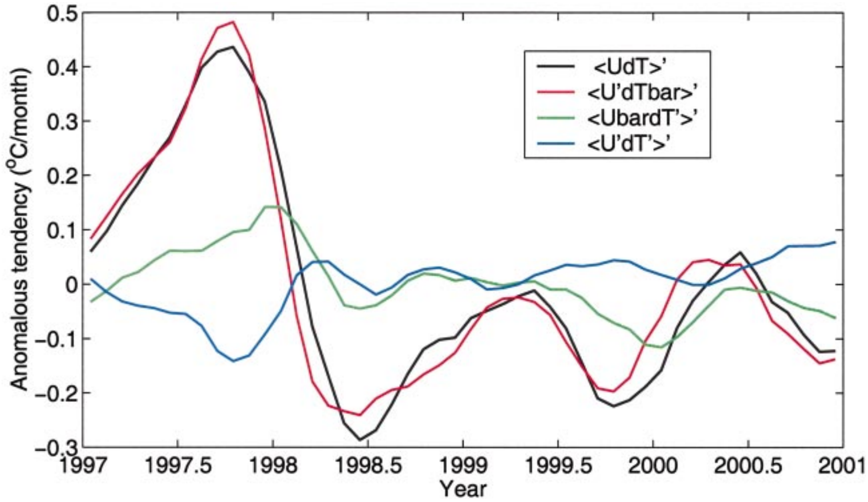

FIG. 5. Decomposition of zonal advection of temperature through the western interface (black curve) into the contributions by anomalous flow (red curve), by anomalous temperature difference (green curve), and by both (blue curve).

sense of their relative importance. Vertical advection (through the bottom face at 50-m depth), also causing warming (cooling) during El Niño (La Niña), is larger than zonal advection. Meridional advection, however, is generally smaller than zonal advection.

As shown by the dashed curve in Fig. 3b, the traditional formulation results in an anomalous cooling (i.e., negative) tendency,

$$\left[-\iiint_D (u\partial T/\partial x)\ dx\ dy\ dz\right]' \bigg/ V_D,$$

during El Niño (from 1997 to mid-1998) and an anomalous warming tendency during La Niña (from mid-1998 to early 2000), largely opposite to that shown by the new formulation

$$\left[\iint_{Sw} u(T - T_m)\, dy\, dz/V_D - \iint_{Se} u(T - T_m)\, dy\, dz/V_D\right]'.$$

To further investigate such tendencies, we examine the horizontal distribution of $-\int_{-50}^{0} [(u\partial T/\partial x)\ dz]'/V_D$. Maps of this quantity averaged over December 1997 and December 1998 are shown in Fig. 7. The local tendencies in December 1997 are relatively small (Fig. 7a). Near the latitude bands of 2°–5°N, the values are predominantly negative (though with small magnitudes). For December 1998 (Fig. 7b), however, there are regions that have relatively large positive tendencies—for example, between 2° and 5°N and between 2° and 5°S, with the former being larger. The predominantly positive local tendencies in December 1998 at these latitudes are

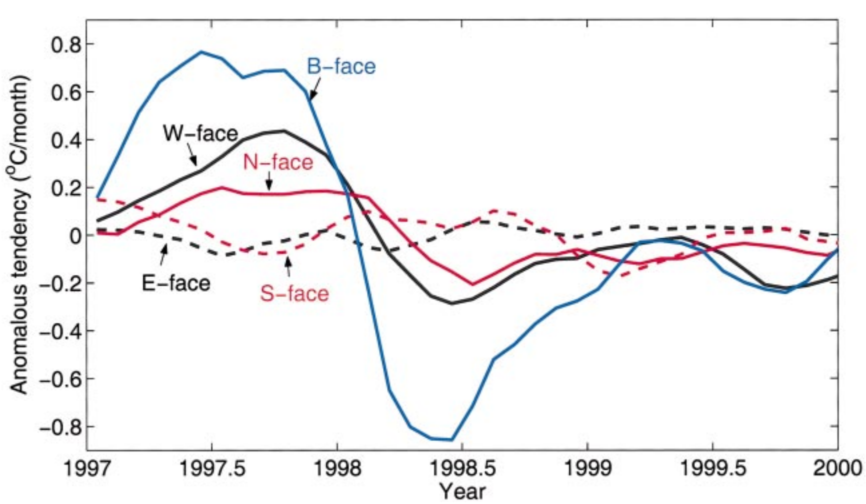

FIG. 6. Anomalies of temperature advection through west and east faces (black), north and south faces (red), and bottom (50-m depth) face (blue).

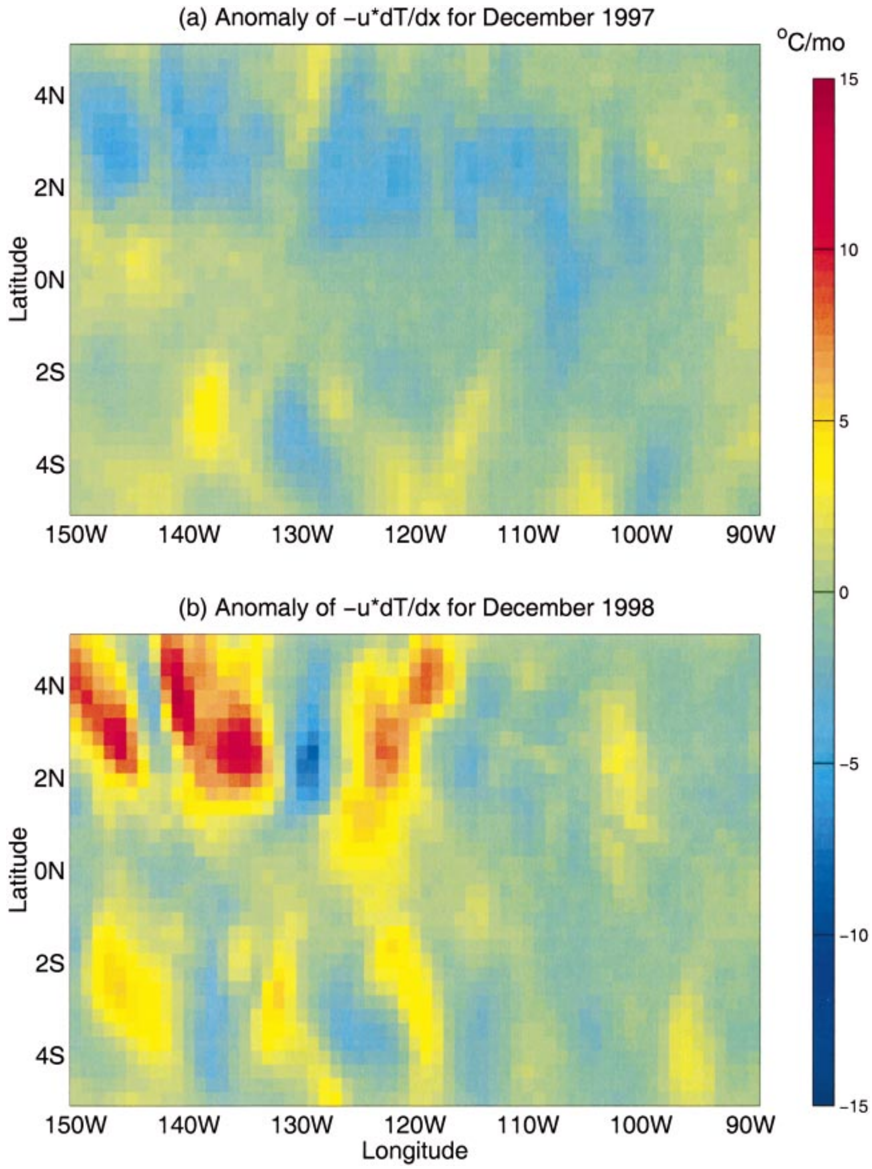

FIG. 7. Top 50-m averages of the anomalies of local zonal advection of temperature averaged over December (a) 1997 and (b) 1998.

associated with tropical instability waves (TIWs) that cause local covariability of u and $\delta T/\delta x$. The average spacing of the alternate patterns of positive and negative tendencies (with the former being dominant) in Fig. 7, about 1000 km, is the approximate wavelength of the TIWs. Since the propagating TIWs have submonthly periods, the monthly averaged tendencies shown in Fig. 7 somewhat smear out the patterns of TIWs.

TIWs are more active during La Niña than during normal condition and are absent during El Niño, which explains the large values in December 1998 but not in December 1997. The small negative tendencies before mid-1998 shown by the dashed curve in Fig. 3b or for December 1997 in Fig. 7a are because ''local warming'' by TIWs is absent. In the sense of anomaly from the averaged seasonal cycle, it is a ''cooling'' effect (anomalously negative tendency). After mid-1998, the anomalously intense TIWs cause relatively large positive anomaly of local advective tendencies. That explains the relatively large positive tendency after mid-1998 shown by the dashed curve in Fig. 3b. Local positive and negative tendencies shown in Fig. 7 or their spatial integration (dashed curve in Fig. 3b) reflect the zonal redistribution of heat within the domain by TIWs. Because such redistribution does not represent an internal source of heat, they should not be considered part of the averaged temperature budget of the domain.

TIWs do travel across the western interface of the

Niño-3 box (e.g., Fig. 7b). This results in variations of zonal velocity and temperature at that interface relative to the mean temperature of the box and thus contributes to $\langle u'\delta T'\rangle'$ (blue curve in Fig. 5). The fact that $\langle u'\delta T'\rangle'$ is anomalously negative in 1997 and positive in 1998–2000 is consistent with the disappearance of TIWs in 1997 and reemergence afterward. However, Fig. 5 shows that $\langle u'\delta T'\rangle'$ is much smaller than $\langle u'\overline{\delta T}\rangle'$, suggesting that the former is not a dominant process for heat advection across the western interface.

Some studies (e.g., Vialard et al. 2001) separate directional contribution of spatially integrated local temperature advection into advection by lower-frequency current and that by ''eddies'' (e.g., TIWs). Despite the decomposition, advection by low-frequency current within the domain still reflects internal redistribution of heat as does the advection by higher-frequency ''eddies.'' Any redistribution process within the integrated domain, regardless of their frequency or wavenumber characteristics, should not be considered as heat sources or sinks that control the total heat content of the domain.

4. Conclusions

The traditional expression of temperature advection $-\mathbf{V}\cdot\nabla T$ describes local advection of temperature. Its spatial integration, when decomposed into contributions along individual directions, includes averaged local advective processes that redistribute heat within the domain of integration. A new formulation of temperature advection is introduced to evaluate effects of external processes. The formulation is expressed as advection of interface temperature referenced to the spatially averaged temperature of the domain. This effectively removes the dependence of the boundary flux form of heat advection on zero-temperature reference.

To illustrate the differences, the two formulations are applied to the analysis of interannual variability of near-surface temperature averaged over the Niño-3 region in the eastern equatorial Pacific as simulated by a data-assimilative OGCM for the period of 1997–2000. The discussion focuses on zonal advection to contrast internal and external advective processes. The new formulation highlights the following zonal process in affecting the heat content of the Niño-3 region: 1) anomalous eastward flow brings warmer water from the west into the Niño-3 region to increase its heat content during El Niño and 2) anomalous westward flow takes out warmer water from the western side of the Niño-3 region to decrease its heat content during La Niña. In contrast, the traditional formulation of zonal advection has a negative (positive) tendency during El Niño (La Niña) that is more or less opposite to the new formulation. This reflects local tendencies associated with tropical instability waves that redistribute heat within the domain. TIWs are absent during El Niño and are anomalously intense during La Niña, resulting in the aforementioned averaged tendencies. TIW process is mostly internal to the Niño-3 region and thus cannot explain the external factors that cause the change in mean temperature of the region.

The results suggest a need for caution in evaluating temperature balance over a large domain. In particular, spatially integrated individual directional contributions of local temperature advection based on the traditional formulation can be dominated by internal processes that redistribute heat within the domain. In contrast, the new formulation quantifies the external advective mechanisms that control the averaged temperature of the domain by explicitly considering boundary processes. The differences illustrate the importance of distinguishing internal redistribution processes from external mechanisms that control the mean temperature of a domain. Although our discussion focuses on the advection of oceanic temperature, the conclusion about local and external processes represented by the two formulations apply to advection of any property in any medium.

Although the subject of this paper is about temperature advection, a few words are in place for heat transport convergence due to mixing for the sake of completeness. The issues for heat advection discussed in this paper are mass conservation and the dependence on zero-temperature reference. In the model, mixing of heat is parameterized through $\mathbf{k}\nabla T$ where $\mathbf{k}$ is the mixing tensor. This parameterization does not involve mass and is independent of zero-temperature reference. Therefore, the issues that concern heat advection are irrelevant to mixing of heat in the model. The difference between internal and external advective processes discussed in this paper is also not an issue to the mixing of heat in the model. This is because the spatial integration of local mixing along a direction is equivalent to boundary mixing in the same direction:

$$\iiint_D \partial(k\partial T/\partial x)/\partial x\, dx\, dy\, dz = \iint_{Se} k\partial T/\partial x\, dy\, dz - \iint_{Sw} k\partial T/\partial x\, dy\, dz,$$

where S is the bounding surface of volume D.

This study pertains to temperature advection on scales larger than the $1° \times 0.3°$ grid size of the model. In reality, there could be subgrid-scale advective process (e.g., subgrid-scale ''stirring'') in the Niño-3 region that is parameterized in $\mathbf{k}\nabla T$ along with other subgrid-scale processes. The model's mixing parameterization does not allow us to decompose this term into advection and other effects. Investigation of subgrid-scale processes is beyond the scope of this paper. Instead, this study aims to quantify advective effects on scales larger than the model's grid resolution.

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